One Millimeter Horizontal Precision Over a 41 Km Baseline Using P-Codeless Data

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High accuracy geodetic solutions at the few ppb level have become fairly standard with data from a global network of P-code Global Positioning System (GPS) receivers. Used as a measurement tool, it has numerous scientific applications including the monitoring of crustal motion, volcanic and post-seismic uplift, co- and post-seismic displacements in fault zones and media delay calibration and monitoring. The GPS signal has been encrypted repeatedly in the recent past and may become so permanently in the future, thus potentially reducing some of its utility as a geodetic tool. In the current study, a 41 km baseline was measured in P-codeless mode using two Rogue SNR-8000 (TurboRogue) GPS receivers. P-codeless baseline solutions were obtained yielding daily repeatabilities of 1 mm and 8 mm in the horizontal and vertical directions, The analysis strategy included utilizing P-code based precise GPS ephemerides from standard global network solutions, requiring carrier phase integer ambiguity resolutions, and imposing an elevation angle cutoff of 20 degrees. This study indicates that GPS solutions for horizontal components of baselines up to 40 km is fairly independent of signal encryption, assuming that the data has similar quality as compared to P-codeless TurboRogue data. The vertical component is slightly worse compared to P-code solutions for comparable baselines and this may be a current limitation for GPS when encryption is turned on.

1. Introduction

In the last decade, GPS have emerged as a low-cost, high-accuracy geodetic tool for measuring tectonic motion, volcanic uplift, post-glacial rebound, earth orientation, sea-floor geodesy, co- and post-seismic motion, for monitoring and calibrating the troposphere and the ionosphere, and for numerous navigation and positioning applications. Recent results show that 1 cm-level geocentric station coordinate accuracies are routinely achievable, assuming the availability of a global network of high precision receivers [Blewitt, et al, 1993]. Currently the GPS Global Network (GGN) contains 45+ dual-band, P-code, GPS receivers of Rogue-type, operated in loose collaboration by a dozen or more international agencies under the auspices of the International GPS Geodetic Service (IGS).

The GPS signals consists of sinusoids modulated by a psudo-random sequence (P-code) allowing for precise tracking of phase changes in addition to range delays, The Rogue receivers in code mode produce L-Band (LB), dual-frequency range (PI and P2) and ful I wavelength phase (L I and L2) observable, in addition to C/A range and phase observable, In recent months, the P-code have been encrypted on several occasions and this may become a permanent feature for GPS signals. The Rogue receivers have the ability to track GPS satellites in a special P-codeless mode, where the unknown code on one frequency band (LB1) is difference off the second band (LB2). This technique is commonly called cross-correlation, It is possible to form four observable from the P-codeless data (similar to the P-code case above, but noisier), again with full wavelength phases, In this letter we have analyzed P-codeless data for a short (41 km) baseline, utilizing the P-code based precise GPS ephemeris available routinely from several processing centers, The goal with this study is to consider the effects of P-codeless data on GPS baseline precision in an attempt to assess the impact of GPS as a geodetic tool when its signal is encrypted.

2. Methods

A. Data Acquisition

Most of the Rogue receivers in the GGN are of the older type, i.e., Rogue SNR-8, 800, or 8C (mini-Rogue). The recent receiver versions Rogue SNR-8000 and 8100 (TurboRogue) has been installed in -15 locations in the GGN so far. In the following we will refer to the former types as Rogue [Thomas, 1988] and to the latter as TurboRogue [Meehan, et al., 1992]. The TurboRogue's have substantially better P-codeless data, as will be shown below, compared to the Rogue. For our study two TurboRogues were used, one located at JPL (on the roof of our office building - JPLO) and the other in Saugus (SAUG), CA, roughly 41 km North-West of JPL. Data were acquired from the two stations for nine contiguous days between 17-25 December, 1992, For reference frame control fiducial stations were added to the solution, The two stations were located at Goldstone (GOLD), California, and Fairbanks (FAIR), Alaska, providing GPS P-Code data from Rogue receivers.

B. Cross-Correlation Data

The TurboRogue can extract differential group-delay (P2-P1) and phase (L2-L1) with P-code encryption (anti-spoofing) on or off, Full P-code tracking provides highest precision phase and pseudorange measurements and is the default tracking mode for TurboRogue. However, whenever the receiver discovers that a GPS satellite has encrypted its P-code, P-codeless tracking is the automatic fall-back mode. This mode is not entirely codeless since the receiver continues to track the C/A code normally, hence the name P-codeless rather than just codeless, The result is normal code processing of the C/A signal and a digital cross-correlation of the the two code frequency bands. This produces P2-P1 pseudorange and L1 -L2 phase observable. These observables are a measure of the differential ionospheric effects between the two P-code frequency bands, The differential observable can be used with the C/A measurements to construct four data types with similar characteristics to P-code observable, but with more noise. The TurboRogue takes advantage of the fact that both code bands have the same code modulation/encryption (sometimes called Y-code). Because each carrier has identical modulation, the LB1 signal can be cross correlated with the LB2 signal, resulting in both differential phase measurements (L1 -L2) and group delay measurements (P1-P2).

The Rogue and TurboRogue P-codeless processing generates four data types, C/A phase and range and LI-L2 and PI -P2. The C/A phase on the TurboRogue has the same frequency as P-code L1 and may be labelled L1'. The C/A phase is rotated by a quarter cycle to be in-phase with L1 and being a C/A observable it has a higher SNR than L1. Hence, the P-codeless L1' phase observable is actually in all respects similar to L1 P-code phase but of higher quality, The C/A range measurement is less precise than the P-code range measurement although the TurboRogue employs a "narrow-lag" C/A correlator [Meehan, et al., 1992] which provides C/A range measurements comparable to P-code. For P-codeless processing, the C/A range may be relabeled as PI'. The L2 and P2 measurements may be constructed by differencing C/A and differential observable, generating two synthetic observable, L2' and P2'. The noise on the cross-correlation measurements is very sensitive to changes in antenna gain. As a result, the scatter on the P-codeless LB2 observable tends to vary significantly with satellite elevation angle.

TurboRogue receivers employ a specially designed choke ring antenna to minimize the effects of multipath. One of the features of the choke ring that helps reduce multipath effects is a somewhat sharp gain cutoff at lower elevation angles, With ground based geodetic applications, most multipath comes from low reflecting objects. For satell ites at low elevations the choke ring design reduces the amplitude of both the direct signal from the satellite and the reflected multipath signal. When tracking in full P-code mode, the SNR is relatively high regardless of elevation angle and multipath tends to dominate, However, P-codeless SNR is significantly affected by reduced antenna gain and therefore, at low elevation angles, noise rather than multipath tends to dominate measurement error. Figure 1 shows the difference between LB2 phase for P-code (L2) and P-codeless (L2') versus elevation angle for the TurboRogue. At 20 degrees the rms scatter is still below 5 mm, but at 15 degrees the scatter is already at 10 mm, The dominance of data noise over multipath in P-codeless mode is illustrated in figure 2, where the range and phase delay multipath plus noise scatter on LB2 is plotted versus elevation angle for the Rogue and the TurboRogue. The pseudorange multipath is typically 20-40 cm, however, here the scatter is several meters for both Rogues and TurboRogues, completely dominated by noise. The peak-to-peak scatter is ~4 m at 40 degrees increasing to 8+ m at 20 degrees for the TurboRogue. A satellite at 20 degrees elevation will have about 10 times the LB2 phase and range noise as one at zenith for the TurboRogue, From Figure 2 we can also compare Rogue and TurboRogue P-codeless LB2 phase and pseudorange noise as a function of elevation angle. In this example, the pseudorange scatter have been reduced by a factor of ~3 for the TurboRogue compared with the Rogue. Similar comparisons show that generally the P-codeless phase and pseudorange data noise levels have been reduced by a factor of 2-3 for both frequency bands for the TurboRogue versus the Rogue.

The above results will affect data processing in several ways, Poorer quality pseudorange data can put more stress on automatic data editing programs as well as solutions requiring carrier phase ambiguity resolution. The TurboRogue pseudorange appears to be good enough for robust processing with the automatic editor used in GIPSY (using the TurboEdit algortihm, see Blewitt, 1990). For the cases when the quality of the carrier phase measurements is poor (for example at low elevation angles during P-codeless mode) it becomes necessary to raise the elevation cutoff angles (or to provide weighting of the data by elevation). The data noise in GIPSY's Kalman-type filter is generally 10 mm for P-code phase data, Figure 1 indicate that TurboRogue P-codeless phase data may be kept at the same data noise level.

C. Analysis Method

JPL's routine GPS Global analysis currently utilizes 45+ GPS Rogue receivers for its daily solutions and yields precise GPS ephemerides, Earth orientation, station coordinates, station clock solutions, tropospheric estimates among the daily data products. The GPS orbits are precise to ~30 cm as shown by standard 3-dimensional RSS overlap analysis [Blewitt, et al., 1993], These P-code derived orbits from the GGN were held fixed in our 2-station codeless baseline analysis. Hence, data from the local stations were not used to improve the global orbits, based on the assumption that such an enhancement would be insignificant.

Apart from the fixed orbits, the P-codeless data were processed in a similar manner to the usual GGN data analysis for P-code data. The data reduction used the GIPSY software and is outlined in Heflin et al. [1992] and references therein. The P-codeless phase and range observable from the two frequency bands were combined into ionospheric free range and phase observables (LC' and PC') to remove first order ionospheric delays. The pseudorange data was averaged and phase smoothed over 5 minute data intervals and the phase data was simply decimated to the same data interval. The station coordinates at SAUG and JPLO were estimated as constants as were the carrier phase biases, Clocks were estimated as white process noise (hence eliminated) and the tropospheric delays were solved for using a random walk stochastic model [Lichten, 1990]. The station coordinates for GOLD and FAIR were held fixed in the 1991 ITRF reference frame at epoch 1992.5. The elevation angle cutoff for the P-codeless analysis was chosen to be 20 degrees, which is somewhat higher compared to the usual cutoff of 15 degrees. A horizon mask of 20 degrees was selected based on the fairly rapid degradation of the rms scatter shown earlier. Carrier phase integer ambiguities were resolved for the P-codeless baseline,

3. Results

Postfit residuals where computed for P-codeless phase and range observable, Figure 3 shows the LC' and PC' residuals versus time for satellite 23, with rms scatters of 6 mm and 57 cm respectively. The corresponding P-code residuals for the same TurboRogue receiver, time and satellite were 3 mm and 25 cm respectively, indicating roughly a factor of 2 increase in noise with P-codeless data,

Figure 4 show the daily repeatabilities in the horizontal components for the 41 -km baseline, The rms scatter is 1.5 mm and 3.0 mm before carrier phase integer ambiguity resolution (squares) in the north and east components respectively and 8.0 mm in the vertical direction. After ambiguity resolution (circles), the north and east components show repeatabilities of about a millimeter (0.6 mm E, 1.3 mm N). The vertical repeatability remains the similar (7.9 mm) after ambiguity resolution. The factor of 3 improvement along the east component with ambiguity resolution agrees with results obtained in the past analysis of ambiguity resolution [Blewitt, 1989]. The success of the ambiguity resolution indicates that the P-codeless pseudorange precision was sufficient for the widelane technique used, however, resolving the widelane ambiguities below about 20 degrees may be difficult based on the rapid degradation of pseudorange precision at lower elevations.

GPS solutions usually yield poorer results for vertical components (due to less sensitivity to this component for the down-looking GPS technique) and our result above is typical in that respect, However, repeatabilities of 8 mm are not quite as good as usually expected of P-code data from short baselines such as this one. The vertical baseline component derives significant strength from lower elevation data and hence may be more sensitive to lower SNR and higher data noise for lower elevation P-codeless data. Note also that the elevation angle cutoff was 20 degrees, which is 5 degrees higher than normally used for P-code data, hence some data strength may have been lost due to the higher cutoff.

4. Discussion and Conclusions

The results shown here indicate that few mm precision or better is possible to obtain with P-codeless data of TurboRogue quality over a 40+ km baseline. Despite the fact that P-codeless data is significantly noisier than P-code data, the baseline repeatability obtained here with P-codeless data are comparable to earlier P-code solutions, The P-codeless data quality (from the TurboRogue) is good enough such that the standard automatic editing and phase ambiguity resolution processing utilized in GIPSY succeeded. In fact, the baseline precision improved by a factor of ~3 in the East component after ambiguity resolution, similar to earlier results with P-code data. The accuracy of 40+ km P-codeless baselines appears to be primarily limited by modeling (tropospheric errors) and multipath.

The Rogue P-codeless data is a factor of 2-3 noisier compared to TurboRogue data, The major effects of increased data noise are reduced effectiveness of automatic editing and phase ambiguity programs and would probably require substantial modifications to current GPS parameter estimation strategies. Note that ~30 GPS receivers in the GGN are of Rogue type, hence permanent encryption would most likely significantly impact processing and analysis from the Network. For shorter baselines, however, high-accaruacy geodetic work should still be possible in the future, weather or not the GPS signal is encrypted.

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Figure Captions:

Fig. 1. Shown is the difference between P-code and P-codeless L-Band 2 carrier phase versus elevation angle for the TurboRogue. The rms difference is still below 5 mm at 20 degrees, but at 15 degrees the difference has already reached 10 mm.

Fig. 2. A comparison of Rogue and TurboRogue P-codeless L-Band 2 phase and pseudorange noise as a function of elevation angle. Generally the P-codeless phase and pseudorange data noise on both L-Band frequencies are a factor of 2-3 worse for the Rogue versus the TurboRogue.

Fig. 3. Postfit residuals for P-Code and P-Codeless solutions versus time for satellite 23. The P-Codeless rms scatters are 6 mm and 57 cm for phase and range observables respectively, The corresponding P-code residuals are 3 mm and 25 cm respectively, indicating a factor of ~2 increase in noise with P-codeless data.

Fig. 4. Daily estimates of the horizontal components of the 41 -km baseline is shown. The rms scatter is 1.5 mm and 3.0 mm before carrier phase integer ambiguity resolution (squares) in the north and east components respectively and 1 mm in each component after ambiguity resolution (circles). The vertical repeatability remains around 8mm before and after ambiguity resolution.

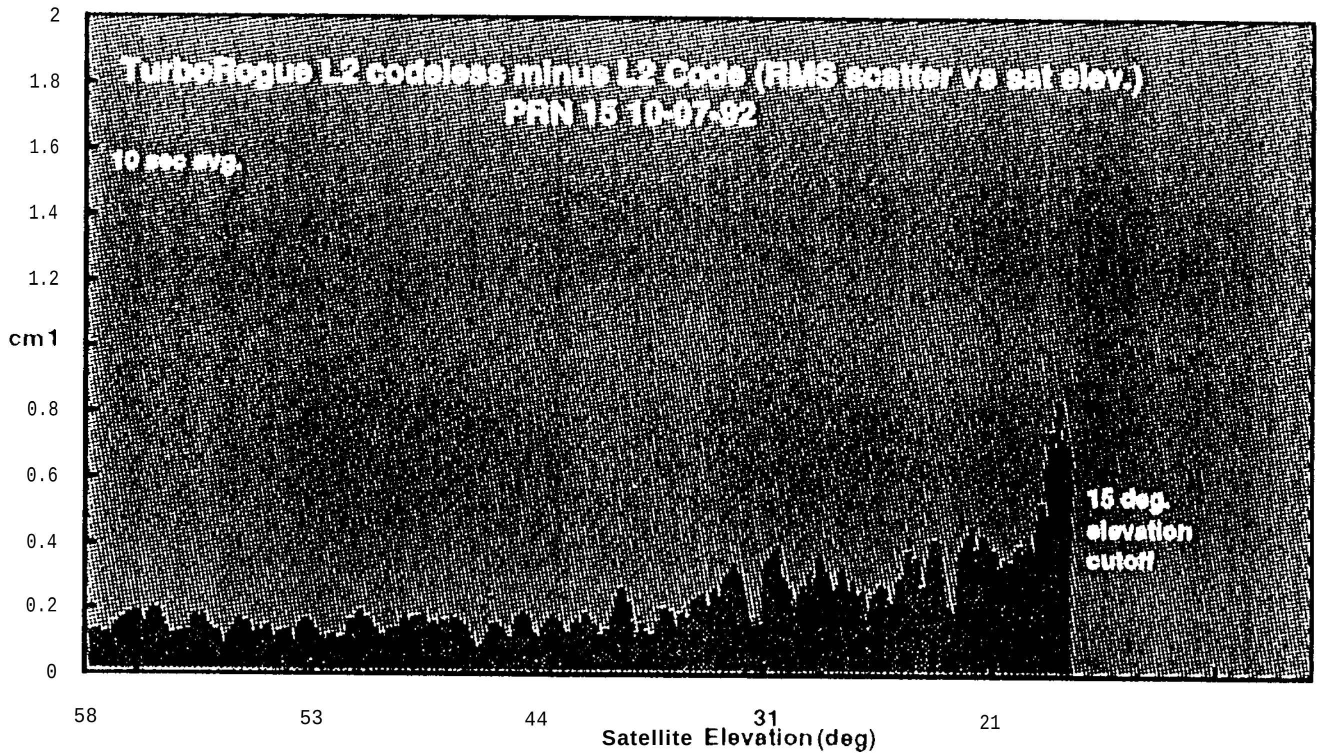

TurboRogue L2 codeless minus L2 Code (RMS scatter vs sat elev.)
PRN 15 10-07-92
10 sec avg.
15 deg. elevation cutoff
cm
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
58
53
44
31
21
Satellite Elevation (deg)

Figure 1

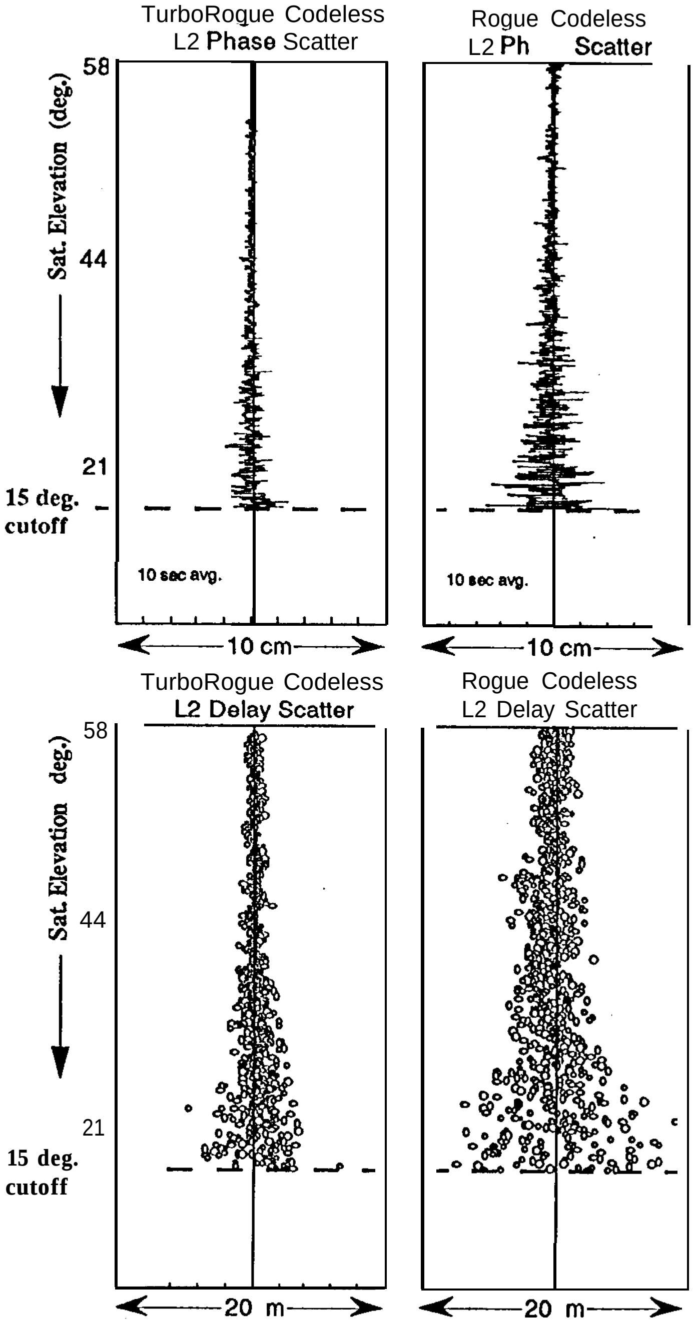
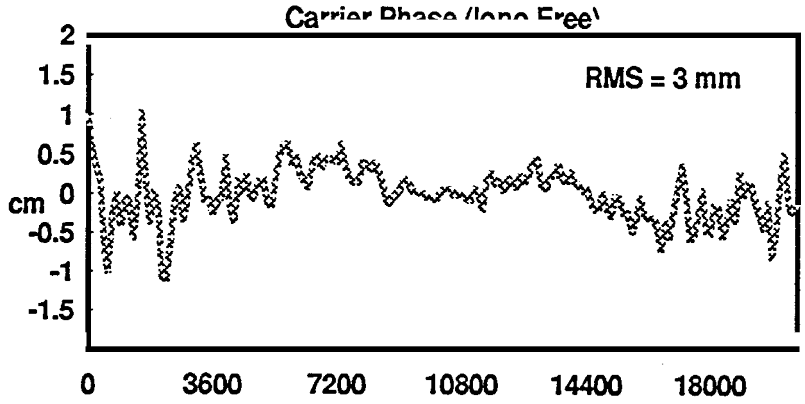
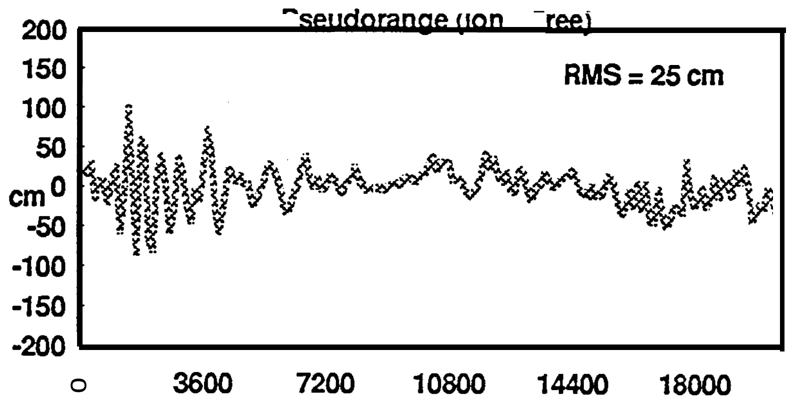

TurboRogue Codeless
L2 Phase Scatter
Rogue Codeless
L2 Ph Scatter
58
44
21
Sat. Elevation (deg.)
15 deg. cutoff
10 sec avg.
10 sec avg.
10 cm
10 cm
TurboRogue Codeless
L2 Delay Scatter
Rogue Codeless
L2 Delay Scatter
58
44
21
Sat. Elevation deg.)
15 deg. cutoff
20 m
20 m

Fig 2.

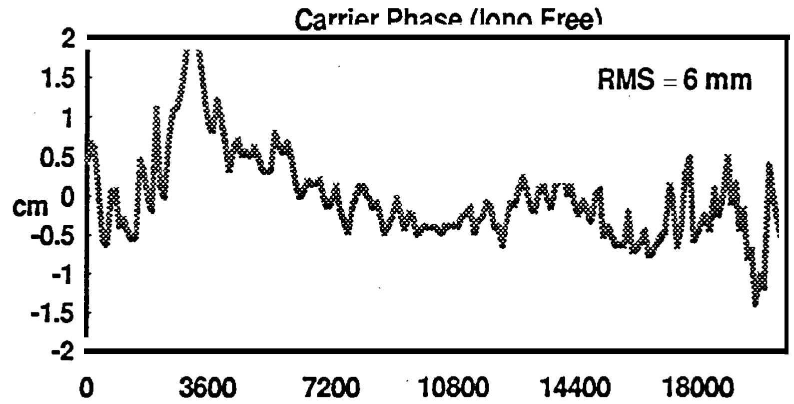
Post-fit Residuals
GPS 23 @ JPL

P-code Data





P-Codeless Data



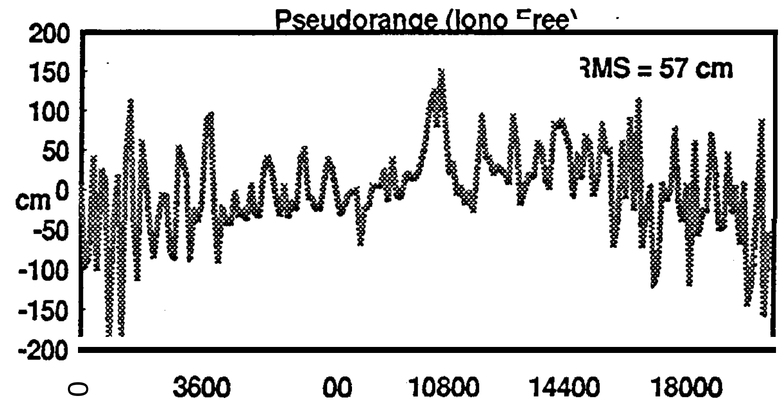
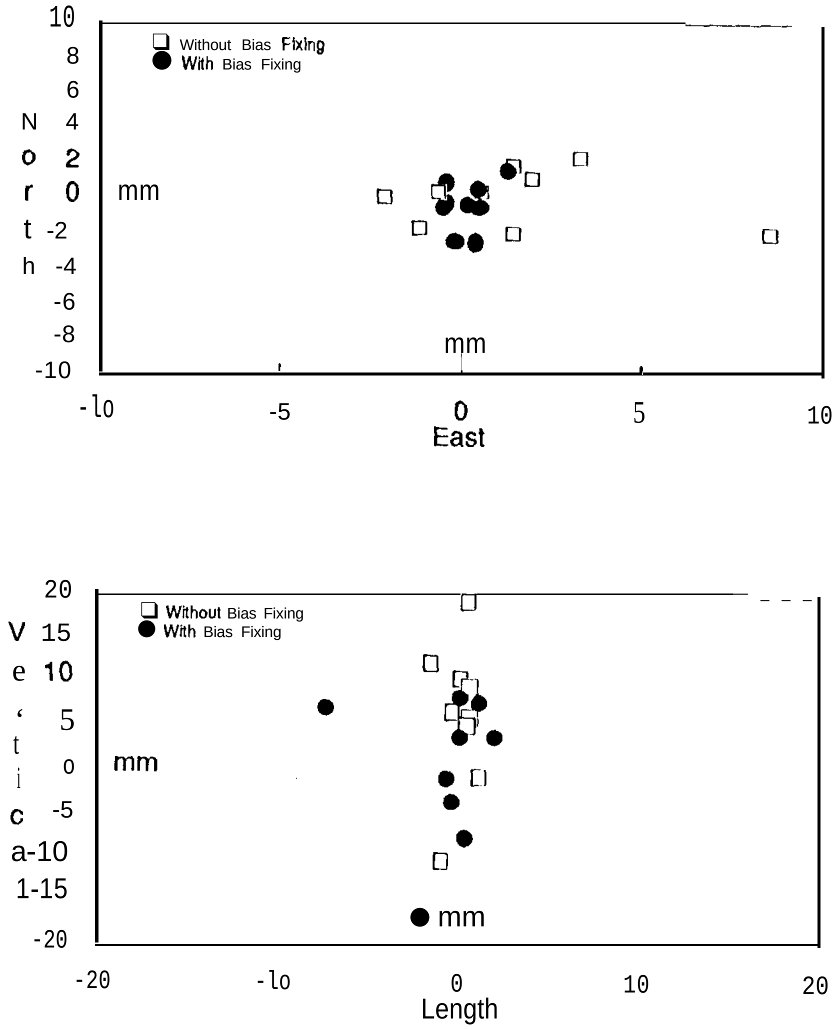


Figure 3


Without Bias Fixing
With Bias Fixing
North
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-10
-5
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5
10
Without Bias Fixing
With Bias Fixing
Vertical
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Length
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-10
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Figure 4